High-Pressure Flame Visualization of Autoignition and Flashback Phenomena With a Liquid-Fuel Spray

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NASA

HIGH-PRESSURE FLAME VISUALIZATION OF AUTOIGNITION AND FLASHBACK
PHENOMENA WITH A LIQUID-FUEL SPRAY

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SUMMARY

A study was undertaken to determine the effect of boundary layers on auto-
ignition and flashback for premixed Jet-A fuel in a unique high-pressure win-
dowed test facility. A plate was placed in the center of the fuel/air stream
to establish a boundary layer. Four experimental configurations were tested:
a 24.5-centimeter-long plate with either a pointed leading edge, a rounded
edge or an edge with a 0.317-centimeter step, or the duct without the plate.
Experiments at an equivalence ratio ranging from 0.4 to 0.9 were performed at
pressures to 2500 kPa (25 atm) at temperatures of 600, 645, and 700 K and
velocities to 115 meters per second. Flame shapes were observed during flash-
back and autoignition using high speed cinematography. Flashback and auto-
ignition limits were determined.

INTRODUCTION

The high combustor inlet air temperatures and pressures of advanced high-
pressure-ratio engines increase the emissions of oxides of nitrogen (NO_x)
pollutants. An order-of-magnitude reduction in oxides of nitrogen and an im-
provement in combustor performance and durability can be achieved by premixing
and prevaporizing the fuel/air mixture and by burning at lean equivalence
ratios in the primary zone of the combustor. This concept is being investi-
gated in the Advanced Low Emission Combustor (ALEC) Program at the NASA Lewis
Research Center (ref.1). One of the constraints for this concept is that as
the inlet air temperature and pressure increase, the autoignition delay times
decrease and flashback velocities increase. Thus, the mixing and vaporizing
process must be completed rapidly before autoignition occurs. If the flame
flashes into the premixing tube, NO_x emissions increase rapidly and exten-
sive damage can occur to the premixing tube and the combustor.

If the residence time of a fuel/air mixture exceeds the ignition delay
time, then spontaneous ignition of the mixture will occur. This is the clas-
sical definition of autoignition. If the flow velocity of the fuel/air mix-
ture is less than the flame velocity, then the flame will propagate upstream.
This is the classical flashback phenomena. Autoignition is a function of inlet
air temperature and pressure, equivalence ratio, and boundary layer conditions;
and knowledge is required to properly design the premixing tube. To prevent
flashback, the velocity past the flameholder downstream of the premixing tube
must exceed the flashback velocity.

Spadaccini has reviewed the literature on autoignition (ref. 2) and con-
cluded that previous investigations were not successful in isolating and con-
trolling the experimental variables over ranges representative of conditions

in an advanced gas turbine engine. Thus, autoignition delay data reported in the literature require careful interpretation with respect to the effect of test apparatus and measurement technique on the results. Some results are contradictory. For example, Stringer, Clarke, and Clarke (ref. 3) found only a minor effect of equivalence ratio and air velocity on autoignition delay times for an "Avtur" fuel similar to Jet-A for pressures between 3000 and 6000 kPa. Mestre and Ducourneau (ref. 4) and Ducourneau (ref. 5) measured the auto-ignition delay times for kerosene which is similar to Jet-A. However, over a similar temperature range but at lower pressures (500 to 1200 kPa), they reported a large effect of equivalence ratio on autoignition delay times as well as an effect of injector configuration.

Spadaccini has designed and operated an autoignition apparatus which was intended to provide the quantitative data necessary to answer some of these questions concerning autoignition (ref. 6). However, this apparatus was not designed to address boundary layer effects. In fact, the walls were cooled in an effort to prevent wall boundary-layer autoignition. In addition, this facility did not have a high-pressure window for visual and photographic observation of the test section. With a viewing capability during autoignition, one can observe whether droplet burning is involved or whether the fuel/air was completely vaporized and mixed prior to autoignition.

Flashback is another constraint on the design of premixing-prevaporizing combustors. There have been no studies of flashback reported for the pressures expected to be encountered in future high-technology combustors. However, Marek et al (ref. 7) and Roffe and Venkataramani (ref. 8) have obtained flashback data at pressures up to 10 atmospheres. Plee and Mellor (ref. 9) have reviewed flashback reported in premixing, prevaporizing chambers. They concluded that "classical flashback, which results from the flame exceeding the fuel/air velocity in either the tube boundary layer or in the free stream, has not been observed in noncatalytic combustion systems burning hydrocarbon fuels. Instead, autoignition of the air stream, flame propagation through reversed flow fields, and preignition of the fuel/air mixture in separated flow regions of the mixing tube are responsible for the reported phenomena." In addition to these causes, flashback may also be caused by pressure oscillations in the flow system. Flashback resulting from a pressure/ flow pulsation would be expected to occur at a significantly different reference velocity than flashback through a steady flowing mixture. In an actual flowing combustion system, it is difficult to determine which of these effects is producing the flashback.

A windowed test section is desirable for studying flashback phenomena for two reasons: (1) for observing where flame propagation occurs during flashback - in the free stream, in the boundary layer of the test duct, or in the boundary layer of a test plate placed in the duct, and (2) for observing the propagation velocity of the flame.

An experimental investigation was conducted in a high-pressure windowed test facility to determine the autoignition and flashback characteristic of Jet-A fuel. This paper presents the results of this study over pressures from 500 to 2500 kPa, inlet temperatures from 600 to 700K, inlet air velocities from 20 to 115 meters/sec, and equivalence ratios from 0.4 to 0.9.

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APPARATUS

A unique windowed test rig was operated in a high pressure, 2500 kPa, combustion test facility to determine the conditions for autoignition or flashback for premixed Jet-A fuel. A schematic of the test rig is shown in figure 1.

The non-vitiated preheated air entered a large plenum chamber of 0.3 m^3 volume and then flowed into a bellmouth entrance section which was 64 centimeters long by 7.62 centimeters exit diameter. Fuel was injected through seven holes located on three 3.175 mm tubes spraying downstream. The 0.76 mm holes were arranged in a hexagonal pattern 11.0 mm apart; the tubes were 9.5 mm apart, see inset on figure 1. The fuel was injected more in the center of the duct to keep it off the walls and out of the boundary layers of the glass mixing tube as much as possible. The fuel injector pressure drop ranged from 500 to 80 000 kPa.

The premixing duct consisted of a thin, 2 mm thick quartz tube which was 7.62 cm in diameter. The smooth tube enabled plug flow of the fuel/air mixture, allowed observation of the flame front and provided thermal protection for the pressure vessel. The thin quartz tube was able to sustain thermal shock extremely well and could withstand pressure pulses as high as 300 kPa. The quartz tube was convectively cooled with an independently controlled air supply which mixed with the fuel/air mixture at a downstream station just before the afterburner and provided automatic balancing of the pressure across the quartz tube. The upstream end of the tube was sealed with a teflon o-ring.

Visual observations of the flame were made through windows capable of withstanding high pressure. The windows were 10 centimeters in diameter and 5 centimeters thick and were located on opposite sides of the duct, 47.5 centimeters downstream of the fuel injector.

The test plate had replaceable leading edges and was inserted from the downstream end of the quartz tube with the tip centered in the window. The plate was 24.5 centimeters long by 7.3 centimeters wide by 1.27 centimeters thick. Five thermocouples were inserted on the centerline of the plate - on the top and bottom at 14.5 centimeters from the tip, the top and bottom at 22.5 centimeters from the tip and one in the wake region. These thermocouples were used to determine the temperature of the plate at flashback and the position of the flame on the plate when it was not visible in the window. The data were recorded automatically at intervals of 1.5 seconds using a digitizer and a minicomputer. A radiometer port was used to automatically initiate the data recording system when flame propagation occurred. Data were also recorded by manual initiation before and after flashback.

Experiments were conducted on three leading edge geometries as shown in figure 2: a 20° pointed edge, a bullet nose, and a 3.17 mm step. These leading edges provided various boundary layer conditions on the surface.

Downstream of the plate a close-coupled, nitrogen-cooled, high response pressure transducer (20 000 Hz) measured the pressure perturbations and pulses. A spectrum analyzer determined the frequency of the signal.

Finally the fuel/air mixture entered a piloted afterburner where the flameholder consisted of six water cooled tubes, 2.54 centimeters in diameter

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which penetrated 6.0 centimeters into the combustor. The mixture entered a water spray quench section before being throttled through a back pressure valve.

A cutaway isometric view of the apparatus showing the simulated flame and spray regions is shown in figure 3.

PROCEDURE

For a typical experimental run, the inlet temperature, airflow, pressure and fuel flow were set. Then the pressure was gradually increased, stopping at particular values for at least two minutes to record stable operating points. As the pressure was increased the flow velocity decreases and the residence time in the duct increases until a point was reached where flame appears in the window caused by either flashback or autoignition. The condition where flame appeared in the window was defined as an unstable operating point. After an unstable point was determined the test section fuel was shut off. The conditions were repeated by setting the pressure and then gradually increasing the fuel flow to an equivalence ratio as high as 0.9 while maintaining pressure constant to see if the flames would flash or autoignite.

The shape of the flame was recorded using high speed (500 frames per second) cinematography.

RESULTS AND DISCUSSION

Conditions of flame instability were determined for four configurations – an open duct with no plate present, a plate with either a pointed leading edge, a bullet nose or a 0.317 centimeter step. The results are presented for each configuration.

Open Duct Data

The flame can appear in the mixing duct by flashback from the afterburner flame stabilizer, by autoignition or by autoignition followed by flashback. Stability data was taken without the test plate present to obtain baseline data for comparison with results with the plate present. Unstable conditions (flashback and/or autoignition) are represented as solid symbols in figure 4 for three nominal inlet air temperature levels of 600, 645, and 700 K. Open symbols represent stable conditions at a given reference velocity without the flame appearing for at least two minutes. The reference velocity is the duct velocity at the inlet temperature and pressure. The equivalence ratio was varied from 0.4 to as high as 0.9 with little change in the stable conditions.

Flashback occurred at reference velocities below 22 meters per second at 600 K. Some variation of the flashback velocity with pressure was present. This variation could have been caused by changes in fineness of atomization, rate of droplet vaporization, and rate of mixing of the fuel and air within the duct.

Flashback was preceded by large pressure oscillations. In this system oscillations of ±2 kPa were observed with just the afterburner pilot fuel

nozzle operating. With the test section fuel on, a ±15 kPa pressure oscilla-
tion existed with a frequency of 23 hertz. As pressure was increased a criti-
cal velocity was reached when the fluctuations would grow suddenly as high as
±250 kPa accompanied by flashback. Even though the amplitude of these fluctu-
ations increased, the dominant frequency remained constant. The unstable
points (solid symbols) shown in figure 4 indicate that the flame appeared in
the window. This coincided with the conditions of maximum pressure oscilla-
tions. The instability may be a result of the acoustic coupling of the premix
duct with the downstream afterburner flame. The occurrence of oscillations
preceding flashback in a premixing-prevaporizing facility was also reported by
Coats (ref. 10). All flowing combustion systems include some dominant fre-
quencies. If the velocity in a combustion system is such that pressure fluc-
tuations at the dominant frequencies are amplified, large pressure fluctuations
occur which can precipitate flashback.

Shown in figure 4(b), at 645 K the flashback velocity was still 22 meters
per second and was nearly independent of pressure. The autoignition limits
previously determined for Jet-A fuel in reference 7 are shown as a dashed line
in figure 4. In reference 7, the ignition delay time τ was found to be
inversely proportional to pressure, P; that is

$$\tau = \frac{L}{V} = \frac{3.4 \times 10^{-4} \exp (7700/T)}{P}$$

or

$$V = \frac{LP}{3.4 \times 10^{-4} \exp (7700/T)} \tag{1}$$

where V is the tube velocity in meters per second, L is the reference length
in meters, P is the pressure in kPa and T is temperature in degrees Kelvin.
The airstream velocity required to prevent autoignition is linear with pres-
sure. The reference length used in the plots is the length of the premixing
tube from the fuel injector to the center of the window which was 0.47 meters.
This length was used because the flame could only be observed in the window
area. At 600 K (fig. 4(a)), the unstable condition was the result of flash-
back because the velocity was above the velocity where autoignition would be
expected to occur. At 645 K (fig. 4(b)), the instability was again the result
of flashback with instability occurring at a higher velocity than in figure
4(a). In figure 4(c), since the reference velocity at which autoignition oc-
curred at 700 K is a function of pressure, autoignition occurred rather than
flashback.

Photographs of the flame propagation are shown in figure 5. These pic-
tures are frames from high speed movies (500 frames per second) with an ex-
posure of 1/1500 of a second. The exposure time is one third the framing
rate, thus for very fast events there was a possibility that the event would
not be seen. Photographs for 700 K are not presented because the high speed
film did not capture the motion of the flame front across the window at these
conditions.

The photographs in figure 5 show the flame propagating along the walls of
the glass tube during flashback. The flow is from left to right. This

probably was caused by the lower velocity at the walls, or by the instability of a flame in the boundary layer of the lower wall. The degree of vaporization and mixing quality were not measured in these experiments but no droplets were observed in the tube at any of the operating conditions nor was wall wetting observed.

After flashback or autoignition the walls of the quartz tube were completely covered with soot. However, after operation at 700 K for short periods of time, the soot could be burned off. The presence of soot on the walls did not change the flashback point.

Pointed Plate Data

The flashback and autoignition data for the plate with the pointed leading edge are shown in figure 6. At 600 K (fig. 6(a)), the flashback velocity does not differ from the values determined without the plate present. In addition, the pressure oscillations at 23 hertz were present before flashback as had occurred without the plate present. This suggests that the flashback was more a coupling of the pressure oscillations to the flow in the premixing duct rather than a boundary layer instability.

Under some conditions the flame could be stabilized in the wake of the plate as determined by thermocouples. The flame would propagate into the wake region and would burn stably. This data is shown as half-solid symbols in figure 6(a). As the velocity was reduced, flashback into the window would occur. When the flame flashed into the boundary layer of the plate, plate heating would occur. When the plate temperature exceeded 1200 K, fuel flow was automatically stopped to prevent plate overtemperature. When the plate cooled down the fuel flow was restarted. It was not possible to maintain a stable flame on the plate surfaces for any length of time because the plate was uncooled and would heat up rapidly.

In addition to the lower velocity in the region of the plate boundary layer which was not present in the open duct tests, it was noticed that with continuous fuel flow the plate was cooled as much as 40 K. As noted on figure 6(b), with continuous fuel flow the velocity could be lowered below the open duct results (4b) by about 6 meters per second before flashback. However, if the fuel was stopped and the plate allowed to heat up to freestream conditions and then restarted, flashback would occur at the higher velocities shown in figure 6(b). The autoignition lines are the predictions of reference 7. Agreement between the predictions and data is not very good for the 700K data as shown in figure 6(c). Autoignition occurred at a much higher velocity than with the open duct. Whether autoignition occurred in the wake of the plate or in the expansion zone followed by flashback in the boundary layers could not be determined because of the speed of the event. At 700 K it was not possible to keep the flame burning only in the wake region.

At 645 K, examination of figure 6(b) shows that at 1750 kPa the instability could be caused by flashback or by autoignition followed by flashback because the conditions are very close. Examination of the movie sequences at 1175 kPa show that either flashback or autoignition did occur. As shown in figure 7(a), flashback along the test plate occurred, indicated by flame propagation into the windowed area. The flame proceeded along the plate very

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rapidly because the boundary layer of the surface has the lowest velocity and because the plate has the highest fuel concentration since it is located in the center of the duct. The flame continued to propagate even upstream of the plate indicating that a pressure pulse was present. As shown in the sequences of figure 7(b), autoignition occurred at the stagnation point followed by propagation. The nonuniform growth and movement of the flame region indicates that the fuel and air were not uniformly mixed.

Bullet Nose Plate Data

The flashback and autoignition data for the plate with the semicircular leading edge are shown in figure 8. The velocity required to prevent flashback was higher than that with the pointed leading edge. During flashback, pressure oscillations were still present and the dominant frequency was again 23 Hertz. The velocity at autoignition was the highest of any of the configurations tested.

From the high speed movies (fig. 9(a)), it was noted that a separation bubble was occurring near the tip, artificially thickening the boundary layer. In addition the fuel was impinging on the nose and accumulating in the separation bubble. This separated region resulted in the increase in flashback velocity and a large increase in the velocity required to prevent autoignition (700 K data).

Frames from the high speed movies indicated that at 645 K (figs. 9(a) and (b)), flashback was occurring along the surface of the plate and was coupled with a pressure wave. Some frames showing the autoignition at the higher temperature of 700 K were obtained. In figure 9(c) the flame has ignited on the lower surface of the plate and propagated along the boundary layer. Flashback across the window occurred in the next frame. Droplet burning is clearly evident in this sequence with droplets moving from the burned boundary layer into the unburned region. In figure 9(d), droplet burning again is evident with the flame propagating to the fuel injector. The unmixed nature of fuel/air mixture is also clearly apparent.

Stepped Plate Data

A flow step was added using a 0.317 cm step to determine the increase in instability caused by a separated region in the flow. The flashback and auto-ignition data are shown in figure 10. As with the other configurations, the reference velocity reported is the open duct value. However, the plate and step cause a 26 percent area blockage which produced a higher velocity along the plate. The flashback velocities obtained are comparable to the open duct results rather than being significantly higher as anticipated. Flashback was again accompanied by a 23 hertz pressure oscillation suggesting that the dominant effect is an acoustic-coupled instability rather than a boundary-layer effect.

Flashback or autoignition followed by flashback of the flame into the step region was observed and is shown in figure 11. However when this occurred the plate temperature would increase rapidly producing automatic shut-down of the test section fuel. Because of this effect limited data were obtained for this configuration.

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CONCLUDING REMARKS

The prevention of flashback and autoignition at conditions of high inlet pressure and temperature, while still achieving a completely vaporized and well mixed fuel/air mixture, will be a problem for lean premixed prevaporized combustors. Gas turbine combustors operate at reference velocities of 20 to 25 meters/sec. and with area blockages of 50 to 75 percent. This would give a velocity past a flameholder of at least 40 meters/sec. which would be adequate to prevent flashback if no oscillations, separated regions or wakes existed upstream of the flameholders. However, perturbations of the system can cause rapid pressure pulses, resultant flow disturbance, and flashback or autoignition. Oscillations will also create fuel/air ratio variations in a premix passage which may result in increasing amplitude waves. It is expected that all premixing tubes will be subject to acoustic coupled phenomena, that is, pressure wave propagation into the premix tube which will affect the airflow and the local fuel/air ratio of the mixture. This may change the conditions for flashback.

Analytical modeling of flashback and autoignition is very complex, especially accounting for time oscillations and droplets impinging on the plate. Current modeling efforts have not predicted these results.

SUMMARY OF RESULTS

An experimental investigation was conducted to determine the effect of submerged surfaces on autoignition and flashback conditions for a fuel-lean, premixed stream of Jet-A fuel and air. A 24.5 centimeter long test plate with three different leading edges – pointed nose, bullet nose, and stepped nose – was inserted in the stream. The conditions for flashback/autoignition were compared with tests without the plate present. Tests were performed at pressures to 2500 kPa, at temperatures of 600, 645, and 700 K, velocities to 115 meters per second, and equivalence ratios ranging from 0.4 to 0.9. The results are summarized as follows:

1.   In all cases flashback was preceded by pressure oscillations in the duct and the flashback velocity did not vary significantly with configuration. Flashback occurred at velocities of less than 25 meters per second with no test plate present. At 600 and 645 K, flashback was not very sensitive to inlet temperature and pressure over the range of conditions tested.

2.   At 700 K, autoignition was accompanied by flashback in the test plate boundary layer. Inserting the test plate required doubling the velocity to prevent flame instability. Regions of flow separation resulted in increased mixture residence time and led to autoignition. Droplet burning was observed after autoignition at high inlet temperatures and pressures.

3.   The use of the windowed test section along with high speed motion pictures did prove useful for determining what was occurring within the premixing duct during autoignition and/or flashback. The quartz tube liner performed very well and could withstand pressure pulsations and high flame temperatures.

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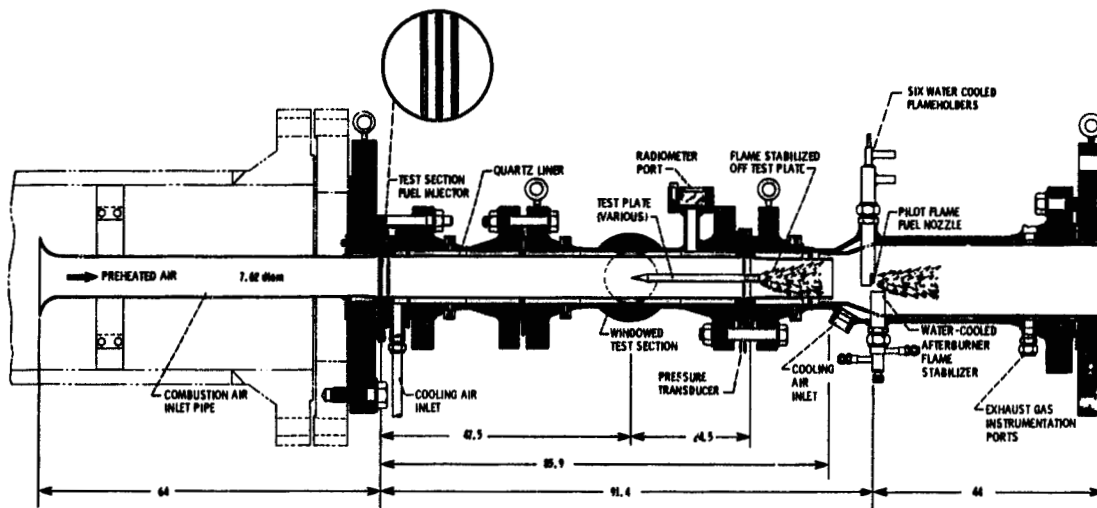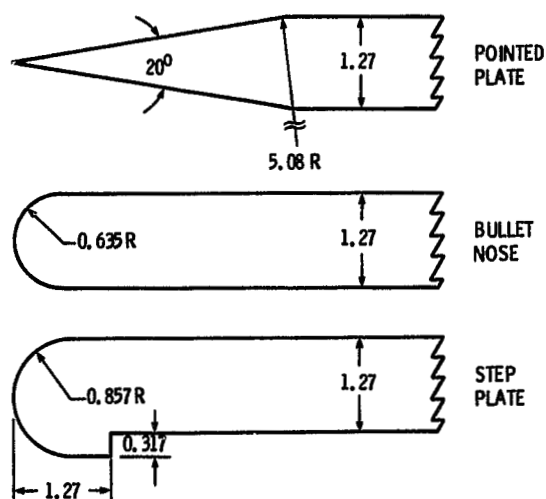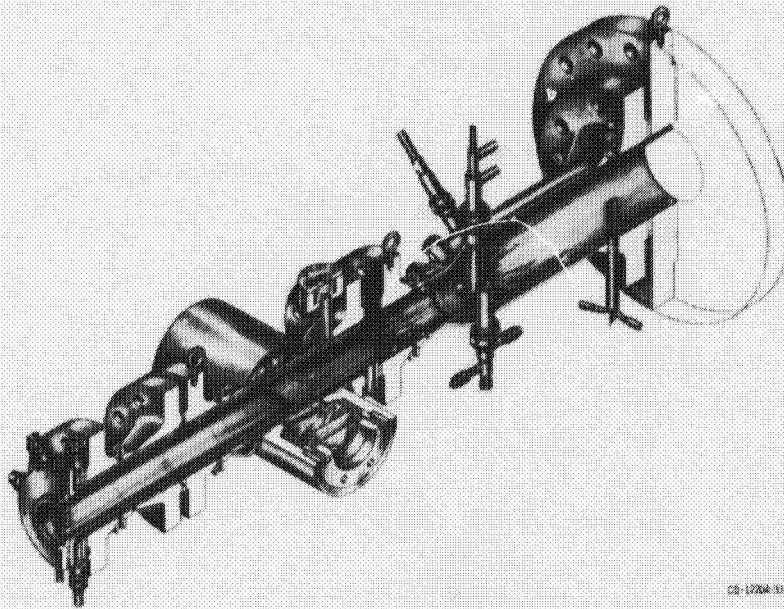Figure 1. - Test rig for autoignition/flashback study. (Dimensions are in cm.)

Figure 2. - Leading edge configurations. (Dimensions are in cm.)

CD-12204-33

Figure 3. - Cutaway view of test apparatus.

(a) Temperature, 600 K.

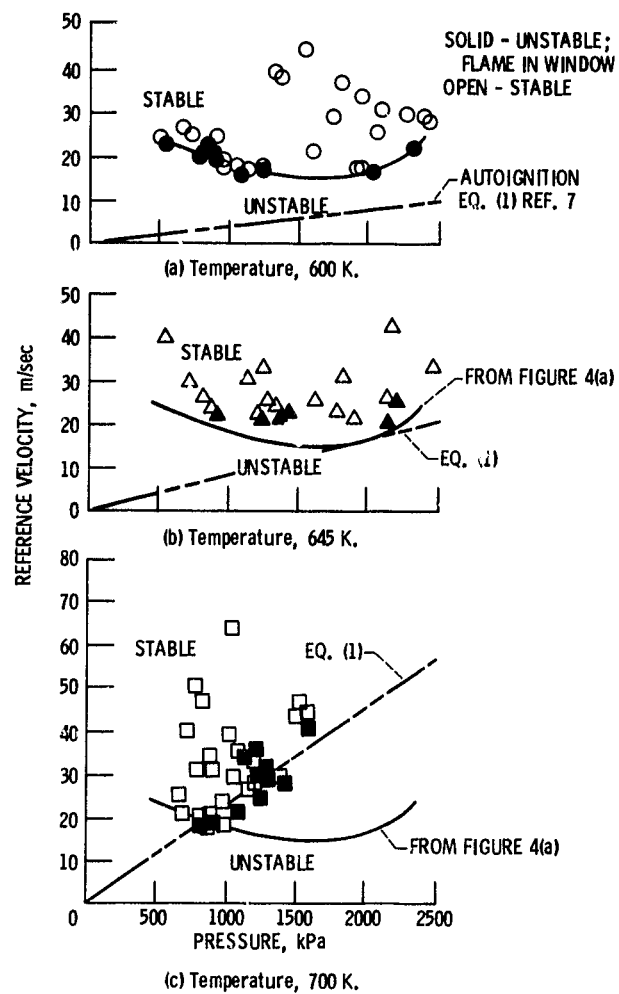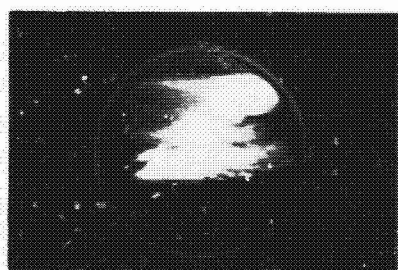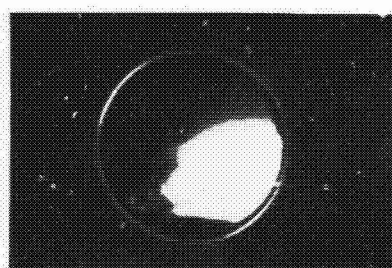(b) Temperature, 645 K.

(c) Temperature, 700 K.

Figure 4. - Stability data for the no plate
configuration.

(a) Pressure 1170 kPa, 600 K.

(b) Pressure 2090 kPa, 640 K.

(c) Pressure 2090 kPa, 640 K.
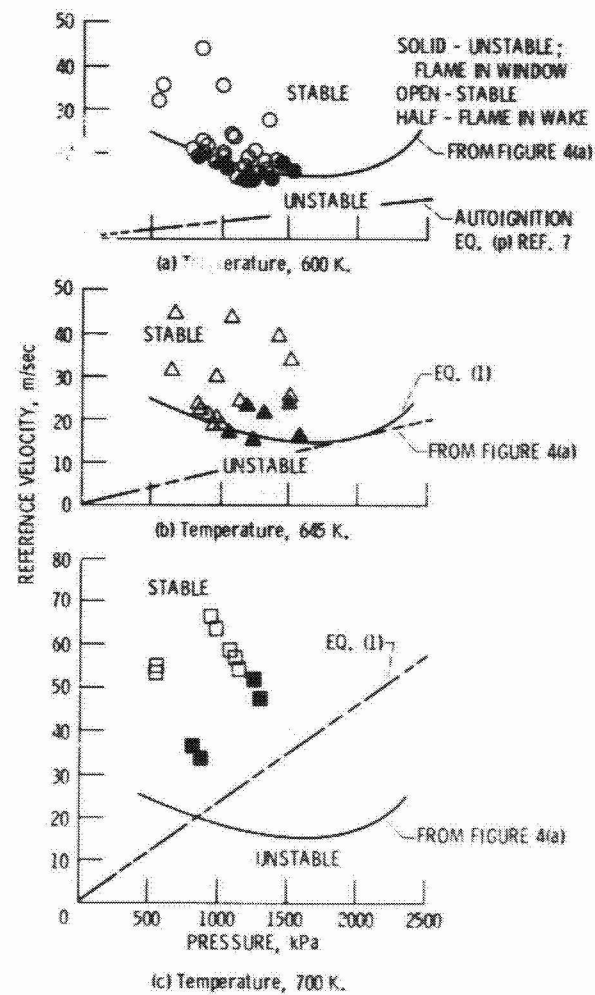
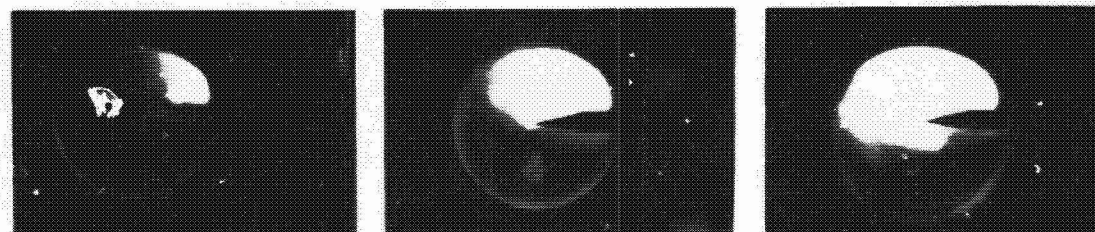Figure 5. - Flashback through tube boundary layer - with no plate.

SOLID - UNSTABLE;
FLAME IN WINDOW
OPEN - STABLE
HALF - FLAME IN WAKE
FROM FIGURE 4(a)

STABLE

UNSTABLE

AUTOIGNITION
EQ. (p) REF. 7

(a) Temperature, 600 K.

STABLE

EQ. (1)

FROM FIGURE 4(a)

UNSTABLE

(b) Temperature, 645 K.

STABLE

EQ. (1)

FROM FIGURE 4(a)

UNSTABLE

REFERENCE VELOCITY, m/sec

PRESSURE, kPa

(c) Temperature, 700 K.

Figure 6. - Stability data for pointed plate.

(a) Flashback sequence.

(b) Autoignition sequence at plate tip.

Figure 7. – Flashback through plate boundary layer pointed tip present pressure 1175 kPa, 640 K.
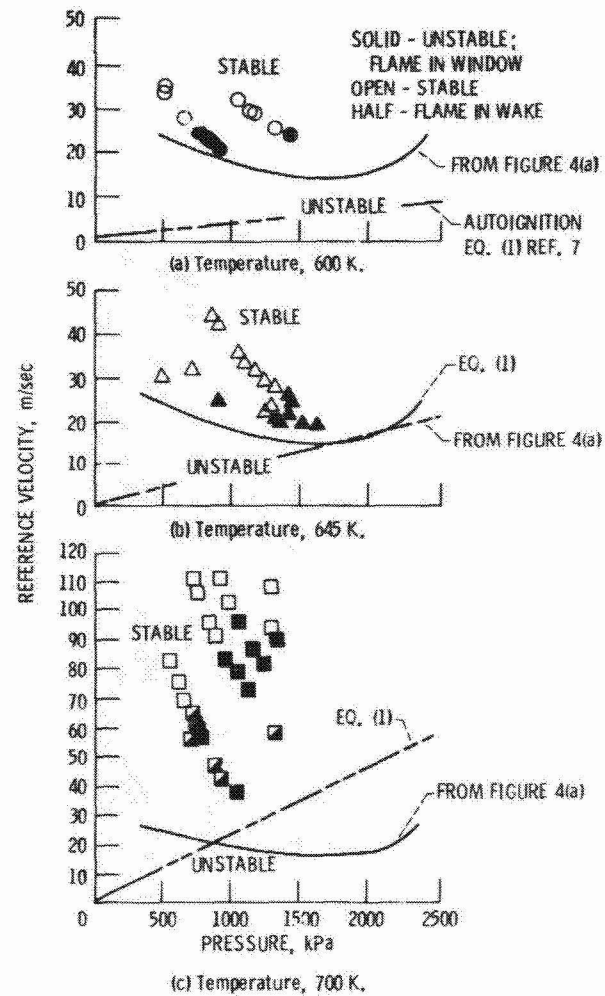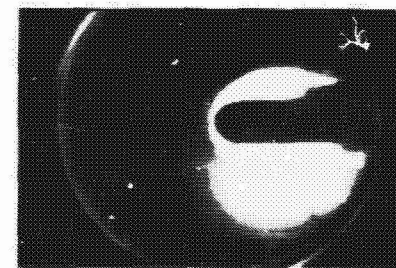
Figure 8. – Stability data for bullet nose plate.

(a) Temperature, 600 K.

(b) Temperature, 645 K.

(c) Temperature, 700 K.

SOLID – UNSTABLE;
FLAME IN WINDOW
OPEN – STABLE
HALF – FLAME IN WAKE

(a) 895 kPa, 644 K.

(b) 1280 kPa, 644 K.

(c) 1309 kPa, 700 K 50 m/sec.

(d) 1033 kPa, 700 K, 40 m/sec.

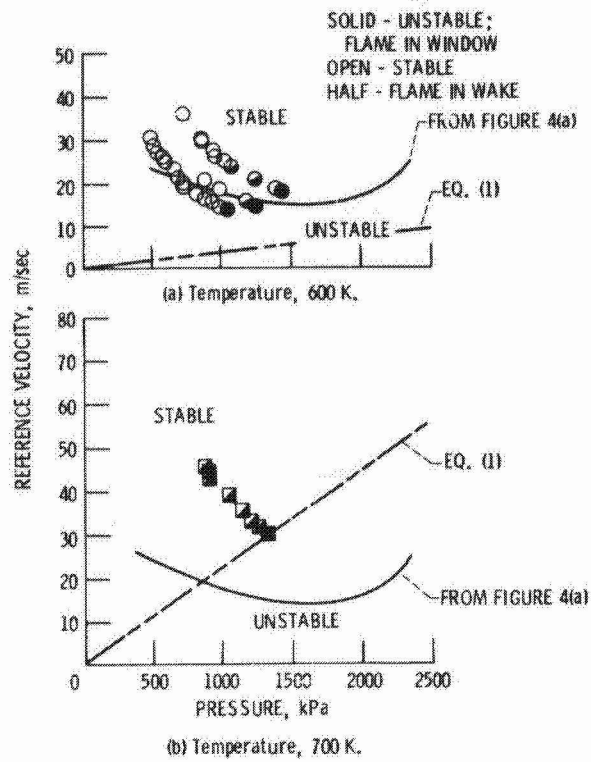Figure 9. – Flashback or autoignition with bullet nose.
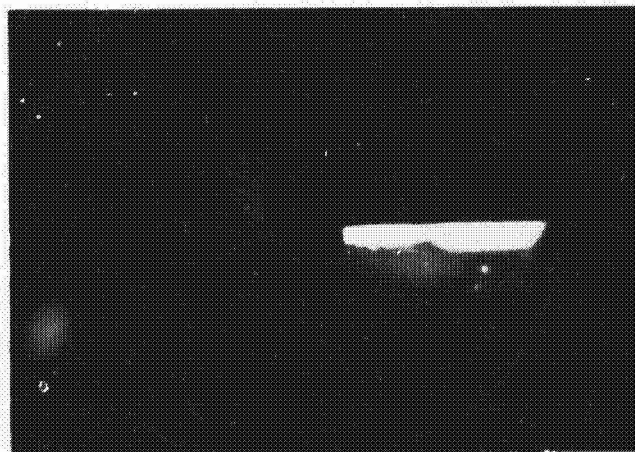
Figure 10. – Stability data for step plate.

Figure 11. – Flashback into wake of step. Pressure 1033 kPa, temperature 600 K velocity 15 m/sec.